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Greenhouse impact due to different peat fuel utilisation chains in Finland — a life-cycle approach

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Greenhouse impacts of different peat fuel utilisation chains were studied. A life cycle approach was used in order to cover all important emissions and sinks due to activities linked to the peat fuel production and utilisation. Radiative forcing was used to describe the greenhouse impact, and the results are given per one petajoule of energy produced. Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions and sinks were considered. Investigated peat production reserves were pristine peatland (fen), forestry-drained peatland, and cultivated (cropland) peatland. The considered phases of the peat utilisation chain included peat fuel production, storage, transport, combustion and the after-treatment of the cut-away peatland. After-treatment alternatives were afforestation and restoration. The greenhouse impact of a considered peat fuel chain was calculated by subtracting the emissions/sinks of a production reserve in a state of non-utilisation from the emissions/sinks of peat utilisation chain. According to the results, the most climate-friendly peat production chain is cultivated peatland–afforestation. Cultivated peatland has large greenhouse gas emissions and these emissions from the land area are ceased by the removal of the peat layer, when the area is utilised for peat fuel production. If forestry-drained peatland or pristine fen is used for peat fuel production, the greenhouse impacts of these chains are of the order of the greenhouse impact of the utilisation chain for coal. Improvement of peat production and combustion methods can be applied to decrease to some extent the greenhouse effect of peat energy.

Introduction

Peat is an important domestic fuel in Finland. The share of the peat fuel was about 7% of the total primary energy use in 2003. Peat is used especially in medium scale combined heat and power (CHP) plants in industry and municipalities for producing electricity and heat for industrial processes and for district heating of dwellings and other buildings. To some extent, peat is used also for heat production only and for generating electricity in condensing power plants.

Because peat fuel is produced in Finland, its use improves employment and the energy security in Finland, which is highly dependent on imported energy sources such as oil, coal and gas. In the 1970s after the oil crisis a strong extension of peat fuel utilisation started as a measure to reduce the dependency on imported fuels. The peat fuel production fields are mainly located in the central and northern parts of the country, where their impact on local employment can be relatively important.

However, the greenhouse gas emissions from the utilisation of peat for energy are relatively high according to the studies made earlier (Hillebrand 1993, Savolainen *et al.* 1994a, 1994b, Uppenberg *et al.* 2001, Nilsson and Nilsson 2004). Also the Emission Reporting Guidelines made by the Intergovernmental Panel on Climate Change (Houghton *et al.* 1996, Penman *et al.* 2003) give quite high emission factors for peat combustion. The European Union Greenhouse Gas Emission Trading Scheme (EU ETS) and the obligations of the reduction of greenhouse gas emissions under the Kyoto Protocol therefore strongly affect the use of peat fuel.

Climate issues related to the utilisation of peat have been a subject of public debate over the past few years. In Finland, peat is classified as a slowly renewable biomass fuel (Ministry of Trade and Industry 2001). The aim of Finland's National Climate Strategy is that peat would be considered as renewable biomass also in International Statistics such as Statistics of OECD/IEA and Eurostat, where at the moment peat is classified as fossil fuel (Ministry of Trade and Industry 2001). Also in Finland's Greenhouse Gas Inventory for the United Nations Framework Convention on Climate Change (UNFCCC) and in the EU ETS peat is considered comparable to fossil fuels. This classification is in accordance with the Guidelines of IPCC (Houghton *et al.* 1996, Penman *et al.* 2003).

After the first Finnish National Climate Strategy (Ministry of Trade and Industry 2001) a research programme Greenhouse Impact of the use of Peat and Peatlands in Finland was initiated in 2002 in order to produce scientific information on the greenhouse gas fluxes associated with peatlands and their utilisation. The programme has produced under its measurement projects much new information, which can be used in the assessment of the greenhouse impact of energy use of peat.

The objectives of this study were (1) to find the most climate-friendly peat fuel production and utilisation chains, considering the whole life-cycle (i.e. what kind of areas the peat fuel production should be directed to and what kind of after-treatment of the cut-away peat production field would be most climate-friendly), (2) to assess the sensitivity and uncertainty of the results, (3) to compare the greenhouse impact of the energy use of peat with that of the fossil fuels (mainly coal), and (4) to produce new information concerning the energy use of peat for the reporting of greenhouse gas emissions according to the IPCC Guidelines for the UNFCCC.

Assessment model of greenhouse impact for the peat fuel life cycle

The most important anthropogenic greenhouse gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The greenhouse impact due to the increased concentrations of these gases in the atmosphere can be expressed in terms of radiative forcing. Radiative forcing describes the perturbation of the radiation balance of the Earth and it can be seen as the driver of the global warming.

The changes of the CO_2 concentration in the atmosphere can be evaluated using carbon cycle models. The natural carbon cycle consists mainly of two processes. One cycle is between the atmosphere and the ocean, the other between the atmosphere and the terrestrial living and dead organic matter. The CO_2 emissions from fossil fuels or from the terrestrial carbon pools are mixed in the atmosphere and quite rapidly also in the surface layer of the oceans. The transfer of an emission pulse to the deeper and greater water volumes of the ocean is, however, a slow process taking place in a time scale of hundreds of years. Removal of N_2O from the atmosphere is also a slow process, but the lifetime of CH_4 emission in the atmosphere is shorter, in the time scale of about ten years.

The life cycle analysis used in this study aims at assessing the environmental impacts associated with the considered activity "from cradle to grave", from the use of resources and raw materials over the use phase to the treatment of waste etc. However, the greenhouse gas emission inventory made according to the IPCC Guidelines (Houghton *et al*. 1996, Penman *et al*. 2003) aims at assessing the greenhouse gas emissions and sinks which shall be estimated and reported annually to the UNFCCC. The objective is to monitor the annual emissions and sinks by countries in a realistic way. This information is also used to assess how the countries fulfil their national obligations under the Kyoto Protocol. Also the emission estimation for the Emission Trading of European Union follows the IPCC Guidelines.

Phases of the lifecycle assessment (LCA) consist of goal and scope definition, inventory analysis, impacts assessment and interpretation. Critical review and reporting are also an important part of LCA (ISO 14040 1997). When applied to the case of the energy use of peat, this means that the impacts from peat fuel production, peat combustion, and after-treatment of peat production field should be taken into account. In the life-cycle approach, the impacts caused in the past and the impacts to be caused in the future shall be considered if they are linked to the activity considered. In the case of many industrial customer products or agricultural products, like food, the considered time span can be quite short, e.g. some months. In the case of peat fuel, the time span considered is much longer, it can be decades or even centuries, if the after-treatment of the cut-away peatland is counted.

This study is limited to the greenhouse impact of peat fuel utilisation, no other environmental impacts are considered. Only the emissions directly related to the peat utilisation chain were taken into account (the utilisation chain takes into consideration the direct emissions from peat fields, machinery, transportation and combustion but not the emissions, which occur due to the building process of a power plant, production of the working machinery, etc.). The emissions and possible sinks are considered for greenhouse gases CO_2, CH_4 and N_2O. The functional unit of the study is one petajoule (PJ) of peat fuel (combusted in a power plant). This means that the results are expressed per one petajoule (PJ) of peat fuel energy. This is to simplify the study, as there are very many types of power plants with different efficiencies depending on purposes and technologies. This functional unit enables the comparison of the results of different peat utilisation chains which consist of peat fuel production and peatland after-treatment alternatives.

The peat reserve used for the production of the peat fuel has greenhouse gas emissions and sinks already at its state before the peat fuel production. Therefore, the greenhouse impacts of the considered activity, production and combustion of peat fuel are calculated by subtracting the emissions of the non-utilisation case (i.e. reference case), from the case of peat fuel utilisation:

$$I = I^{U} - I^{R} \tag{1}$$

where I is the net greenhouse impact, I^{U} is the impact of greenhouse emissions and sinks in the peat fuel utilisation case and I^{R} the greenhouse impact in the reference case. The greenhouse impact is assumed to be a linear function of net emissions (emissions minus sinks by gas) because the emissions considered are a very small fraction of the global greenhouse gas emissions and sinks. The greenhouse impact is described as radiative forcing (Korhonen *et al*. 1993, Savolainen *et al*. 1994a, 1994b, Monni *et al*. 2003). Radiative forcing takes into account emission histories and slow removal of greenhouse gases from the atmosphere providing a time-dependent view on the greenhouse impact.

The emissions are calculated as a function of time:

$$E_i(t) = E_i^{U}(t) - E_i^{R}(t) \quad (2)$$

where $E_i(t)$ is the net emission of the gas i (CO_2, CH_4, N_2O) at time t caused by the activity considered, $E_i^U(t)$ are the emissions (net emissions meaning here emissions and sinks) of gas i in the case of the utilisation of the peat resource and $E_i^R(t)$ in the reference case of non-utilisation.

In the calculation of atmospheric concentrations and radiative forcing due to the atmospheric concentration, the model REFUGE was used (*see* e.g. Monni *et al*. 2003). REFUGE uses in the calculation of the greenhouse gas i concentration $C_i(T)$ at the time T due to the emissions of the gas i a convolution integral:

$$C_i(T) = \int_0^T E_i(t) f_i(T-t)\,dt + C_{0,i}(T) \quad (3)$$

where f_i is the pulse-response function given by Maier-Reimer and Hasselmann (1987) and $C_{0,i}$ is the background concentration which can be time dependent due to other sources of emissions. CH_4 and N_2O concentrations are described with one-exponential life-time model. The radiative forcing is calculated in REFUGE on the basis of additional concentrations caused by the considered activity. The total radiative forcing I_{RF} due to the three gases considered is roughly the sum of radiative forcings of the different gases:

$$I_{RF}(T) = \mathrm{RF}\left[C_{CO_2}(T), C_{CH_4}(T), C_{N_2O}(T)\right] \quad (4)$$

However, the overlapping of the infrared radiation absorption bands of CH_4 and N_2O is accounted for also in Eq. 4 as given by IPCC (Houghton *et al*. 2001). The radiative forcing due to CH_4 is assumed to include also the forcing due to water vapour input to the stratosphere due to the decay of CH_4.

Peat utilisation chains

The greenhouse impacts of six different peat energy utilisation chains were calculated (Table 1). The description of the considered peat utilisation chains can be seen as the first part of life cycle assessment which consist of the goal and scope definition (ISO 14040 1997).

Peat utilisation chains 1–4 were chosen as the most representative ones in Finnish conditions. Around 25% of the areas in peat production in Finland have been pristine, undisturbed mires (Selin 1999). Pristine fen was chosen to represent the production reserve of undisturbed mires, because fens are more suitable and more commonly utilized for peat fuel production in Finland than bogs. Most (ca. 75%) of the peatlands utilised for peat production in Finland have originally been drained for forestry (Selin 1999). Also in the future the main potential of peat production lies in the previously forestry-drained peatlands (Leinonen and Hillebrand 2000), which cover 4.9 million ha of Finland's land area (Finnish Forest Research Institute 2004).

The area of agricultural organic soils (mull and peat) in Finland is approximately 280 000 ha (Myllys and Sinkkonen 2004, Statistics Finland

Table 1. The examined peat utilisation chains and different phases of chains.

Chain	Production reserve	Production	Final phase	Reference situation
1	Pristine fen	Peat production and combustion	Restoration	Pristine fen
2	Pristine fen	Peat production and combustion	Afforestation	Pristine fen
3	Forestry-drained peatland	Peat production and combustion	Afforestation	Forestry-drained peatland
4	Cultivated peatland	Peat production and combustion	Afforestation	Cultivated peatland
5	Forestry-drained peatland	Advanced peat production and combustion	Afforestation	Forestry-drained peatland
6	Cultivated peatland	Advanced peat production and combustion	Afforestation	Cultivated peatland

2005a), and about 67 000 ha of this area is suitable for peat production (Leinonen and Hillebrand 2000). Afforested agricultural peatland increase this reserve to some extent.

After-treatment alternatives considered were afforestation and restoration. Afforestation is especially interesting, because forests sequester carbon into biomass, which can be utilised e.g. in pulp production. Restoration is taken as an example of natural development towards functional mire ecosystem.

We also studied peat production chains termed the vision chains A and B (chains 5 and 6), based on a new peat production technology. The vision chains were calculated to demonstrate the lowest possible level of the greenhouse impact of peat utilisation if all the emissions of different phases were as low as modern technology may allow and if the peat fuel production were directed into areas which are presently sources of greenhouse gases, such as forestry-drained peatlands, cultivated peatlands or the edges of old peat production areas.

There are three phases in each utilisation chain (Table 1). In the beginning of the peat utilisation chain there is a production reserve, which can be pristine fen, forestry-drained peatland or cultivated peatland (i.e. cropland). The next phase is peat production and combustion, which is the same for all peat utilisation chains but more advanced for chains 5 and 6. It includes emissions from working machines, production field, stockpiles and peat fuel combustion. After the utilisation of peat, the cut-away peatland is either afforested or restored to a functioning peatland ecosystem. In the reference situations the production reserve is kept in its original state and it will develop normally.

Input data for calculations

General

The input data for calculations correspond to the second part of the life cycle assessment called life cycle inventory. The functional unit in this study has been defined to be one petajoule of fuel energy. Specific emissions are usually considered to be grams per megajoule (g MJ^{-1}) or grams per production area (g m^{-2}) per year. All emissions and sinks were converted in the calculations to the functional unit corresponding to grams per petajoule (g PJ^{-1}).

Leinonen and Hillebrand (2000) evaluated that the energy content of peat in one hectare of an average peatland suitable for peat production is 9400 MWh, which corresponds to 3384 MJ m^{-2}. The assumptions made then are that the thickness of the peat layer is 2 m and the average energy density of the peat is 0.47 MWh m^{-3} peat. This gives a peat production area of about 30 ha for one PJ of peat fuel energy. Also other earlier studies (Savolainen *et al*. 1994a, Virtanen *et al*. 2003) support this evaluation. These characterising values of peatland (energy content etc.) mainly come from the Geological Survey of Finland (Virtanen *et al*. 2003).

Radiative forcing is used to describe the greenhouse impact. The different time spans of peat utilisation chain have been assessed to be the following. The production and combustion phase lasts 20 years, and the produced energy amount is one PJ. After the production phase the cut-away peatland is either afforested or restored. Time spans for after-treatments are long, and the impacts are integrated to 100 and 300 years for both after-treatment alternatives.

Peat utilisation chains

This chapter gives an overview of different greenhouse gas fluxes in different phases of the peat utilisation chains, based on numerical estimates of emissions and sinks presented in the Appendix. The calculation of greenhouse impact takes place from the atmosphere point of view: i.e. the gas flux to atmosphere (emission) is presented with positive sign and the gas flux from atmosphere (sink) is presented with negative sign.

Greenhouse gas emissions and sinks of the production reserves of peat fuel vary greatly. Pristine fen is a sink of CO_2 and source of CH_4. Forestry-drained peatland is considered as a source of CO_2, because of the increased rate of aerobic decomposition of peat following water-level drawdown. Cultivated peatland is a strong source of CO_2 and N_2O, but a modest sink of

CH_4. The data and emission factors used in the calculations (Appendix) are based on measurements mainly made in the research programme Greenhouse Impact of the Use of Peat and Peatlands in Finland. Lower and upper limit values (Appendix) are used in the sensitivity analysis of the results.

The peat fuel production area releases CO_2 and CH_4. Peat stockpiles release CO_2 due to the decomposition of peat in stockpiles. Working machines release (includes emissions of transportation to power plant etc.) a minor amount of CO_2 due to the combustion of diesel fuel. The combustion phase of peat production releases nearly 90% of total CO_2 emissions of peat utilisation phase. Combustion phase is also a source of N_2O emissions and a minor source of CH_4 emissions.

Alternative after-treatments have a different kind of greenhouse impacts. Afforestation leads to sequestration of carbon (C) into the growing biomass of trees and ground vegetation, and creates an input of C to the soil through above and underground forest litter. However, the decomposition of residual peat on the soil surface produces relatively high CO_2 emissions, which are assumed to decrease exponentially when the soil C stock decreases and organic matter becomes more resistant to decay. We assumed that the amount of residual peat is 15 000 (0–22 500) g m^{-2}, which equals to about 20 cm thick peat layer. During decomposition of residual peat the amount of C is decreasing exponentially from 15 000 g C m^{-2} to 1200 g C m^{-2} within 300 years. It is assumed that afforestation accumulates carbon in the growing tree stand biomass until the average value of carbon stock over the forest rotation period (i.e. ca. half of the maximum C stock before final cut) is reached. Restoration sequesters carbon, but releases CH_4 as a pristine fen.

Vision chains A and B (5 and 6) present the peat production chains of "forestry-drained peatland–afforestation" and "cultivated peatland–afforestation" in which peat is utilised with modern technologies. In vision chain A (5), peat is produced from forestry-drained peatland, which is a small source of emissions. In vision chain B (6) peat is produced from cultivated peatland, which is a great source of emissions (Appendix). Exploitation of these resources then stops the emissions from the reference situation. Peat is assumed to be produced with a new production method called the biomass drier (Myllylä 2005, Pakkanen 2005) in which one PJ of energy is produced in one year instead of 20 years. We selected parameter values to describe the emissions of the peat utilisation phase in which peat is produced with the new production method and combusted with more advanced combustion technology. Emissions from peat production fields are small (assumed to be zero in calculations) due to the new production method. The emissions from working machines and stockpiles are assumed to be minor (working machines 0.5 g CO_2 MJ^{-1}, stockpiles 0.74 g CO_2 MJ^{-1}). The CO_2 emissions from combustion are assumed to be lower due to drier peat fuel (moisture content 30%) and thus the CO_2 emission factor will be 3% smaller (102.6 g CO_2 MJ^{-1}). The CH_4 and N_2O emission factors from combustion are assumed to be lower due to the improved combustion technology. After-treatment phase of the vision chains is afforestation. The amount of residual peat in the cut-away peatland is very small (in calculation assumed to be zero), practically no peat is left for decaying during the afforestation phase. Fast-growing tree species such as birch (*Betula* sp.) could be used in the afforestation.

Fossil fuel: coal utilisation chain

The greenhouse impact of coal was also studied by means of radiative forcing and from the life cycle point of view. The information about emissions (Table 2) was from ExternE study by Pingoud *et al*. (1997). A pulverised coal boiler (Meri-Pori power plant in Finland) was used in the power generation phase. The emissions of CO_2 and CH_4 of combustion phase were estimated from the general specific emissions of coal. The main parts of emissions of other stages than combustion are assumed to come mainly from Polish coal mines, where especially CH_4 releases are a serious problem (Pingoud *et al.* 1997). The CH_4 emissions are high in Russian and Chinese coal mines as well. The CH_4 emissions from coal mines usually occur when the mines are taken into utilisation, therefore CH_4,

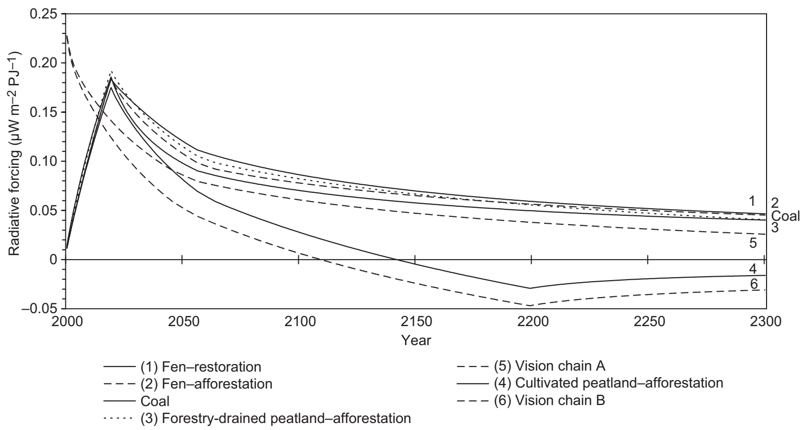

Fig. 1. Radiative forcing of different peat energy chains and coal chain as a function of time. Radiative forcing is presented per global area (m^{-2}).

which has been absorbed in the coal, has already been released from the coal of the old mines. Nowadays however, the CH_4 emissions from coal mines are often captured and burned.

Results

The greenhouse impacts are presented as a function of time (Fig. 1). The radiative forcing can be seen as a calculational heating power in the atmosphere due to greenhouse gas emissions from the considered peat fuel utilisation chain. The considered time span is 300 years (from year 2000 to 2300). The peat production and combustion occurs during the first 20 years, when the radiative forcing increases strongly (Fig. 1). After peat utilisation the after-treatment of the peat production area starts. The consequent decrease in the radiative forcing is due to the carbon transfer from atmosphere to oceans and due to the sequestration of carbon into growing biomass and litter.

The peat energy production chain "fen–restoration" (1) produces the largest greenhouse impact. The greenhouse impacts of other peat chains, "fen–afforestation" (2), and "forestry-drained peatland–afforestation" (3) are almost as large. The lowest impact is produced by the chain based on the utilisation of cultivated peatland (4). The impact of the coal chain is also almost as large as the impact of the chains 1–3. During the production phase (first 20 years, combustion and other emissions from peat production) the "cultivated peatland–afforestation" peat utilisation chain produces similar greenhouse impact as other production chains (excluding vision chains A and B (5 and 6)), but after the production phase the greenhouse impact of this chain turns down quickly and ends up negative within 140 years after production (Fig. 1). The negative radiative forcing results from the ceased greenhouse gas emissions from the production reserve, which in this case would be very high (*see* Appendix).

Vision chains A and B (5 and 6) have the highest greenhouse impacts of the peat and coal utilisation chains in the beginning (during first 15 years) due to exploitation of 1 PJ of peat fuel in one year. However, in the long run vision chain B (6) gives the lowest greenhouse impact of all chains. The greenhouse impact of this chain turns down immediately after production, which takes only one year. Greenhouse impact of vision chain B (6) diminishes and becomes negative within 110 years after production.

The cumulative radiative forcing (Fig. 2) shows the impacts clearer in long time spans.

Table 2. The emissions of coal utilisation chain divided into the power generation phase and other phases of coal fuel cycle (Pingoud *et al.* 1997).

Greenhouse gas	Power generation phase ($g\ MJ^{-1}$)	Other phases of coal fuel cycle ($g\ MJ^{-1}$)	Total ($g\ MJ^{-1}$)
CO_2	92.19	2.99	95.18
CH_4	0.005	0.335	0.34
N_2O	0.002	0.00	0.002

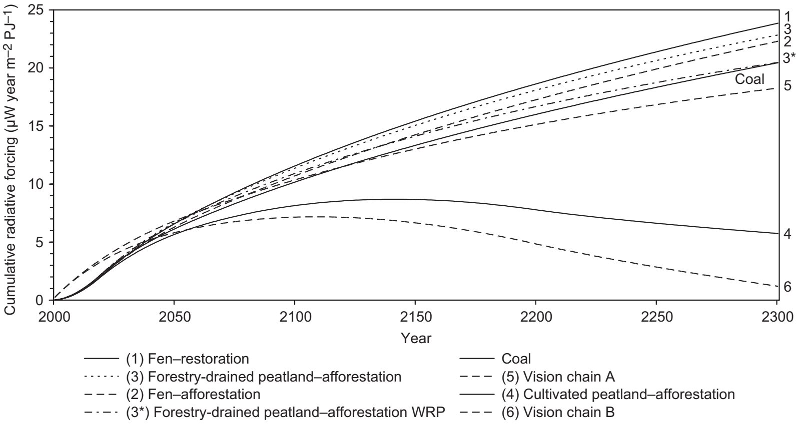

Fig. 2. Cumulative radiative forcing of different peat chains and coal chain as a function of time. Radiative forcing integral is presented per global area (m^{-2}).

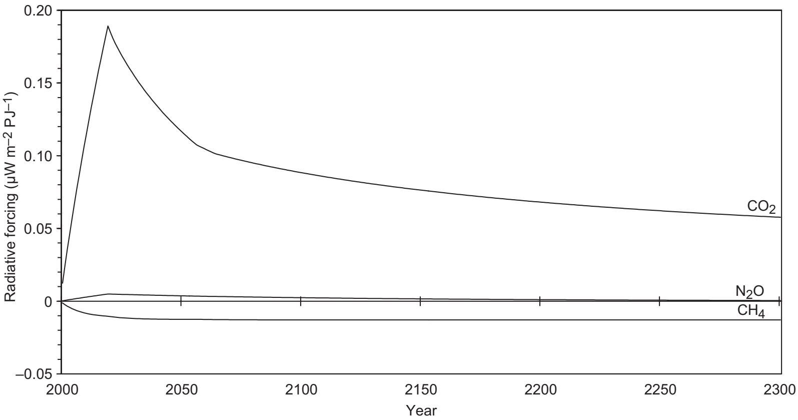

Fig. 3. Radiative forcing of "fen–afforestation" peat utilisation chain (2) by each examined greenhouse gas (CO_2, CH_4 and N_2O) as a function of time.

The cumulative radiative forcing presents the integrated forcing impact or calculational heating energy in the atmosphere due to considered peat fuel chains. The integrated radiative forcing of "cultivated peatland–afforestation" peat production chain 4 starts to decrease about 150 years after production started. None of the other peat production chains ever declines, except vision chain B (6), which almost reaches a neutral greenhouse impact during 300 years after peat production. Also vision chain A (5) has a lower greenhouse impact than chains 1–3 and coal. The results indicate that by improving production and combustion technology in the peat fuel utilisation, the greenhouse impact can be clearly lower.

We also studied one additional peat utilisation chain (Fig. 2), representing "forestry-drained peatland–afforestation" peat production chain 3*, in which no residual peat is left to decompose (WRP = without residual peat). If there is no residual peat, the greenhouse effect of this chain diminishes to the same level as coal during 300 years.

The radiative forcing of "fen–afforestation" peat utilisation chain 2 by each examined greenhouse gas (CO_2, CH_4 and N_2O) is presented in Fig. 3. The greenhouse impact of this chain mainly consists of the emissions of CO_2 caused mainly by the emissions of combustion phase. The impacts of CH_4 and N_2O are small. The negative CH_4 impact is mainly due to the emissions from the pristine fen, which cease when the fen is taken to peat production. The N_2O emissions are mainly caused by the emissions in the combustion phase.

Sensitivity studies

Sensitivity studies help to identify the factors from the use of peat for energy, which has the strongest impact on the radiative forcing. Sensitivity studies are a part of LCA interpretation. As LCA is an iterative process, sensitivity stud-

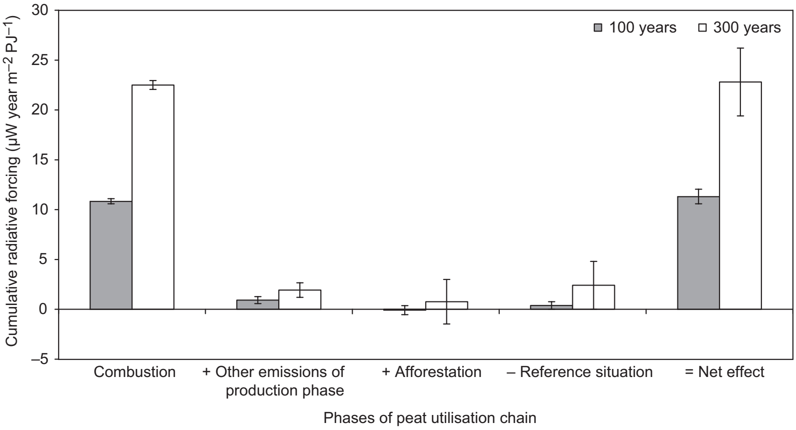

Fig. 4. The cumulative radiative forcing of "forestry-drained peatland–afforestation" peat utilisation chain 3 by each phase calculated for 100 and 300 years. The vertical lines indicate uncertainty due to input data variation.

ies help to identify the factors which need more examination or improvement.

We calculated the cumulative greenhouse impact of "forestry-drained peatland–afforestation" peat utilisation chain 3 by each phase for the integration time spans of 100 and 300 years (Fig. 4). This examination helps to understand the extent of greenhouse impact of each phase of the peat utilisation chain. Also the sensitivity of greenhouse impact of each phase was calculated. These estimations are based on the uncertainty and variation of input values (lower and upper limits, *see* Appendix) and calculated using standard deviations. Different emission and sink terms are assumed to be independent. Vertical lines indicate the possible range of integrated radiative forcing, based on the uncertainty and variation of input values. The greenhouse impact is mainly formed by the emissions from the combustion phase. The emissions from the other production phases have a relatively small influence on the overall greenhouse impact. The uncertainty in the combustion phase is small due to well-known emission factors (the uncertainty of the radiative forcing of the combustion phase is about ± 2%), and it is mainly caused by the uncertainty in the N_2O emission factor. The uncertainty of the other emissions of the production phase is caused mainly by uncertainty of the CO_2 emissions from the peat production area. The greenhouse impact of afforestation is almost neutral (very small sink of carbon) for the 100-year time span because the decomposition of residual peat compensates the effect of carbon sequestered into growing biomass. The uncertainty of this phase is quite large due to the uncertainty of natural processes, especially the amount and decomposition rate of residual peat. The uncertainty of this phase increases with longer examination periods. When the uncertainty is taken into account, the greenhouse impact of afforestation phase could be negative. Also the uncertainty of the reference situation increases over time. The total uncertainty for the 300 years time span is about ± 15% in this calculational case.

Discussion

The greatest contribution to the greenhouse impact of the peat fuel utilisation chain comes from the combustion of the peat fuel. Other contributing phases have a much smaller effect on the total impact. The peat fuel utilisation chains presently in use in Finland (1–3) cause roughly as large a greenhouse impact as the use of coal for energy. The after-treatment alternatives of the cut-away peatlands have relatively small impact on the final results. Instead, the use of cultivated (cropland) peatlands or other areas, which are large sources of greenhouse gases for energy peat production (e.g., peatland previously used for peat harvesting), would create a significantly lower greenhouse impact than coal or the other peat utilisation chains since the peat production would stop the relatively high emissions from this production reserve.

The uncertainties of most emission and sink terms are relatively large with the exception of the CO_2 emission from combustion. However, as the combustion is the main contributor to the final results, the overall uncertainty of the results is moderate. In the case of cropland as the peat fuel production reserve, also the uncertainty of the emissions from the reserve contributes considerably to the total uncertainty. Another factor influencing the results are the long time spans considered. The peat fuel production and combustion take place in about two decades but the rest of the life cycle covers hundreds of years. The long time spans expose the after-treatment alternatives to changes in climate and in land use which make the scenario values for the long time spans quite uncertain.

Uncertainty is also caused by gas concentrations and the radiative forcing models. According to IPCC (Houghton *et al.* 2001) the combined impact of these can be of the order of ±20% depending naturally on the application. However, in this study concentrations and radiative forcing are calculated always with the same model and the absolute values are not of interest but the relative values between various modelled utilisation cases. CO_2 is always the most crucial gas and consequently the impact of the model uncertainty on the relative results can be assumed to be small.

According to the results of this study, the most effective way to lower the greenhouse impact of the peat energy utilisation would be to direct the peat fuel production to the peatlands which are, or have been in agricultural use. Such areas do not form as large landscapes as forestry-drained or pristine fens, so new technological solutions might also be needed to achieve economical feasibility. There are also some other changes which can be used to lower the greenhouse impact of the peat energy. Vision chains A and B of peat production were calculated to show how low the greenhouse impact of peat utilisation chain would be, if all the phases in the peat utilisation chain were optimal.

The results of this study are rather similar to those of earlier studies (Savolainen *et al.* 1994a, 1994b). The gas emission and sink values of the old study do not differ considerably from the measurements done under the Research Programme on Greenhouse Impact of the Use of Peat and Peatlands in Finland. Also Uppenberg *et al.* (2001) assessed the greenhouse impact of peat energy using very similar models as were used in this study and in Savolainen *et al.* (1994a, 1994b). However, Uppenberg *et al.* (2001) included also the renewable wood energy from the cut-away peatland afforestation to the total energy produced, so their result are not based on peat energy alone but also to a considerable degree on renewable wood energy.

Nilsson and Nilsson (2004) also used a methodology very similar to the one applied in our study and in the studies by Savolainen *et al.* (1994a, 1994b). However, many of the input values were different. The values used by Nilsson and Nilsson (2004) for the coal production chain are the same as in Uppenberg *et al.* (2001). For example, the CH_4 emission from the coal chain were assumed to be almost three times higher (1.1 g CH_4 MJ^{-1}) in Nilsson and Nilsson (2004) than in our study (0.34 g CH_4 MJ^{-1}) which increased the greenhouse impact of coal considerably, lowering the relative impact of the peat chains when compared with that of coal. The CH_4 emission in coal chain of this study are from the ExternE study (Pingoud *et al.* 1997) and the value is based on the assessment from Polish coal mines in the 1990s. Technically it is possible to reduce the CH_4 emission further from the level in the Polish mines, and it is quite likely that it will be done. Also the N_2O emissions of the coal production chain were assumed to be higher in Swedish studies (0.01225 g CH_4 MJ^{-1}; Nilsson and Nilsson 2004, Uppenberg *et al.* 2001) than in a Finnish study (0.002 g MJ^{-1}; Pingoud *et al.* 1997).

Other differences compared with Nilsson and Nilsson (2004) arise from the assumptions concerning e.g. emissions from the peat production field, carbon sink in case of restoration as an after-treatment alternative and emissions from forestry-drained peatlands. Nilsson and Nilsson (2004) used values from literature, while in our study the sources were mainly measurements made in Finland under the research programme on Utilisation of Peat and Peatlands in Finland.

Conclusions

According to the results of our study, the most climate-favourable peat energy production chain is based on the use of peat from the peatlands which are in agricultural use. The use of peat energy chains based on the use of peat reserves on forestry-drained peatlands and on pristine fens cause roughly the same greenhouse impact per energy unit produced as the use of coal. However, by improving the production and combustion technology, the greenhouse impact of a peat fuel chain in which peat is produced from forestry-drained peatland is lower than the greenhouse impact of coal.

The sensitivity of the results to the assumptions made in the study is not large. This is due to the fact that the emissions from the fuel burning process are known quite accurately and the other less accurately known contributors do not in absolute terms conribute greatly to the results. However, the emissions from the combustion take place within ca. 20 years in the considered case but the other emission and sink flows extend over 100 or 300 years, and such long time periods can in practice include changes due to changing climate and land-use.

The relatively low greenhouse impact due to the peat energy chain using peat reserve on agricultural land can be reduced further by drying the peat fuel further, lowering the N_2O emissions from the combustion by more advanced technology, by speeding up the peat harvesting, which reduces the emissions from the peat production field, and harvesting practically all peat from the peat production site so that no residual peat is left for decay during the afforestation.

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Appendix. A summary table of all the emissions and sinks of peat utilisation chains.

	Average	Lower	Upper	Source
Production reserves				
Pristine fen				
Carbon dioxide (CO_2, g m^{-2} a^{-1})	–73.34	0	–146.68	Saarnio *et al.* 2007[4)]
Methane (CH_4, g m^{-2} a^{-1})	22.66	14.66	30.66	Saarnio *et al.* 2007[4)]
Nitrous oxide (N_2O, g m^{-2} a^{-1})	0	0	0	Martikainen *et al.* 1993
Forestry-drained peatland				
Carbon dioxide[1)] (CO_2, g m^{-2} a^{-1})	224	0	448	Minkkinen *et al.* 2007a, Minkkinen *et al.* 2007b, T. Penttilä unpubl. data
Methane (CH_4, g m^{-2} a^{-1})	0	0	0	Minkkinen *et al.* 2007a, Minkkinen *et al.* 2007b, T. Penttilä unpubl. data
Nitrous oxide (N_2O, g m^{-2} a^{-1})	0	0	0	Minkkinen *et al.* 2007a, Minkkinen *et al.* 2007b, T. Penttilä unpubl. data
Cultivated (cropland) peatland				
Carbon dioxide (CO_2, g m^{-2} a^{-1})	1760	705	2815	Maljanen *et al.* 2007
Methane (CH_4, g m^{-2} a^{-1})	–0.147	–0.263	–0.031	Maljanen *et al.* 2007
Nitrous oxide (N_2O, g m^{-2} a^{-1})	1.297	0.462	2.132	Maljanen *et al.* 2007
Peat utilisation				
Emissions of peat production field				
Carbon dioxide (CO_2, g MJ^{-1})	6.84	3.42	10.25	Alm *et al.* 2007[4)]
Methane (CH_4, g MJ^{-1})	0.0039	0.0019	0.0058	Statistics Finland 2005b
Emissions of peat stockpile				
Carbon dioxide (CO_2, g MJ^{-1})	1.48	0.74	2.23	Nykänen *et al.* 1996
Working machines				
Carbon dioxide (CO_2, g MJ^{-1})	1	0.5	1.5	Uppenberg *et al.* 2001
Emissions of combustion				
Carbon dioxide (CO_2, g MJ^{-1})	105.9	105.3	106.5	Vesterinen 2003
Methane (CH_4, g MJ^{-1})	0.0085	0.0064	0.0106	Statistics Finland 2005b
Nitrous oxide (N_2O, g MJ^{-1})	0.0128	0.0032	0.0224	Statistics Finland 2005b
Final phase				
Afforestation				
Sequestration of carbon to growing forest[2)] (CO_2, g m^{-2} a^{-1})	–448	–359	–505	T. Penttilä unpubl. data
Accumulation of aboveground forest litter[3)] (CO_2, g m^{-2} a^{-1})	–147	–122	–155	T. Penttilä unpubl. data
Accumulation of belowground forest litter (CO_2, g m^{-2} a^{-1})	–15	0	–22	T. Penttilä unpubl. data
Restoration				
Carbon dioxide (CO_2, g m^{-2} a^{-1})	–121.6	27.9	–271.0	Alm *et al.* 2007[4)]
Methane (CH_4, g m^{-2} a^{-1})	22.66	14.66	30.66	Alm *et al.* 2007[4)]
Nitrous oxide (N_2O, g m^{-2} a^{-1})	0	0	0	Alm *et al.* 2007[4)]

[1)] Includes only soil C changes, not changes in biomass C (tree stand, ground vegetation).
[2)] Forest sequesters carbon until the average value (5.5 kg C m^{-2}) over the rotation is reached.
[3)] Forest litter sequesters carbon until the value 1.8 kg C m^{-2} is reached.
[4)] Given values are preliminary estimates calculated during the programme. Final ones are listed in the given reference.